ASSUMPTIONS INVOLVED IN THE DOCTRINE OF ISOSTATIC COMPENSATION, WITH A NOTE ON HECKER'S DETERMINATION OF GRAVITY AT SEA[1]

WILLIAM HERBERT HOBBS
University of Michigan

CONTENTS

[1] Criticisms of the conception of isostatic compensation from other viewpoints than those here presented are those of Professor T. C. Chamberlin ("Diastrophism and the Formative Processes," *Jour. Geol.*, XXI [October–November, 1913], 577–87; November–December, 1913, pp. 673–82, and succeeding numbers); and those of Professor Joseph Barrell ("The Strength of the Earth's Crust; Part I," *ibid.*, XXII [January–February, 1914], 28–48, and succeeding numbers), which appeared after its formulation. A sharply critical mathematical discussion of Hayford's trial hypothesis, used in fixing the depth of complete compensation, had already been published (Harmon Lewis, "The Theory of Isostacy," *ibid.*, XIX [1911], 603–26). Hayford's rejoinder appeared in the *Journal of Geology* in 1912 (XX, 562–78).

INTRODUCTION

A rigid versus a plastic earth shell.—The doctrine of isostasy is an expression of disbelief that the outer shell of the lithosphere is sufficiently strong to support the protuberances upon its surface. An added idea is that, since it is a failing structure, it is sensitive to surface transfers of rock material and responds with a subsidence beneath freshly loaded areas and with corresponding elevation within denuded districts. It should never be forgotten that this theory was conceived at a time when belief in a liquid interior of our planet was general, and that its adjustment to the modern view of a rigid earth is a matter of the last decade only. Probably the fact which more than any other has compelled geologists to consider the question of possible high plasticity within the earth's outer shell is the great thickness of shallow-water deposits that have been laid down in geosynclines. Although to some extent the recent recognition of the large importance of continental deposits within ancient sedimentary formations has required a modification of earlier assumptions, there is still a call for some explanation of the apparent balance which has been maintained between subsidence and the quantity of deposited material within the basins of sedimentation. Obviously two contrasted hypotheses may be offered. Upon the one hand, it may be assumed that the adjustments in

level are the *cause* of the increased denudation and deposition (doctrine of high rigidity); and, upon the other hand, it may be assumed that these changes in level are the *effect* and not the cause (doctrine of high plasticity—isostasy).

While the name isostasy is of American origin[1] and the crystallization of ideas always connected in time with the providing of a pigeonhole for their assembling has been notably strong in this country, the conception itself is much older and has long occupied the attention of geologists in both Europe and America.[2] It appears to have first found full expression a half-century earlier,[3] and it has ever since played an important rôle in the fields of geodesy and geology. From the failure of astronomic and geodetic locations of position accurately to correspond, and from the "anomalies" of pendulum observations—the so-called "anomalies" of deflection of the vertical and of gravity (Δg.)—it has from the beginning drawn most of its support. Woodward, writing in 1889, says: "In general terms we may say that the difficulty in the way of the use of pendulum observations still hinges on the treatment of local anomalies and on the question of reduction to sea-level."[4]

Pratt's hypothesis.—The remarkable anomalies in the deflection of the plumb line which were discovered in Northern India along the base of the Himalayas led Archdeacon Pratt in 1859[5] to the rather astounding assumption that a mass of less density lies beneath this great protuberance upon the lithosphere. Had the venerable archdeacon conceived the earth to be rigid, as is generally held today, it is not very likely that he would have arrived at this

[1] C. E. Dutton, "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, II (1889), 51–64.

[2] For an excellent summary of the evolution of thought along this line, see F. L. Ransome, "The Great Valley of California: A Criticism of the Theory of Isostasy," *Bull. Dept. Geol. Univ. Cal.*, I, No. 14 (1896), 371–428.

[3] Sir John F. W. Herschel, "Letter to C. Lyell, Esq.," *Phil. Mag.*, II (1837), 212–14.

[4] R. S. Woodward, "The Mathematical Theories of the Earth," *Am. Jour. Sci.* (3), XXXVIII (1889), 341.

[5] John Henry Pratt, "On the Deflection of the Plumb-Line in India Caused by the Attraction of the Himalaya Mountains and of the Elevated Regions Beyond: and Its Modification by the Compensating Effect of a Deficiency of Matter Below the Mountain Mass," *Phil. Trans.*, 1859, pp. 745–96.

conclusion. He assumed further that, since the earth's crust is supposed to be in hydrostatic equilibrium, a level surface must be considered as existing somewhere beneath the crust upon which the pressure of the masses lying above is everywhere the same.[1] This convenient idea of compensation of gravity variations in a deficiency of mass beneath the surface in some cases, and an excess in others, has played a large role in subsequent geodetic studies and is generally referred to as Pratt's hypothesis.

In America the measurements of gravity made by Putnam along the line of the Transcontinental Survey have been studied with much thoroughness by Gilbert, who has been led to the belief that a considerable measure of compensation exists.[2] He says:

> The measurements of gravity appear far more harmonious when the method of reduction postulates isostasy than when it postulates high rigidity. Nearly all the local peculiarities of gravity admit of simple and rational explanation on the theory that the continent as a whole is approximately isostatic. Most of the deviations from the normal arise from excess of matter and are associated with uplift. . . . . The fact that the six stations from Pike's Peak to Salt Lake City, covering a distance of 375 miles, show an average excess of 1,345 rock feet indicates greater sustaining power than is ordinarily ascribed to the lithosphere by the advocates of isostasy [pp. 73–74].

THE HAYFORD CONCEPTION OF ISOSTATIC COMPENSATION

Scope of Dr. Hayford's investigations.—Attention has been focused anew upon the subject of isostasy by the papers of Dr. John F. Hayford, lately inspector of geodetic work and chief of the Computing Division of the United States Coast and Geodetic Survey, and now dean of the College of Engineering at Northwestern University. His investigations have treated of the figure of the earth and isostasy, and are now deservedly well known on the basis of labors extending over a considerable period of years and published in a series of official monographs and briefer summary articles.[3]

[1] This is essentially Helmert's statement of Pratt's hypothesis (*Sitzungsber. Berliner Akad.*, 1908, p. 1060).

[2] G. K. Gilbert, "Notes on the Gravity Determinations Reported by Mr. G. R. Putnam," *Bull. Phil. Soc. Wash.*, XIII (1895), 61–65.

[3] "The Form of the Geoid as Determined by Measurements in the United States," *Report of the Eighth International Geographic Congress, Washington, 1904* (Government

The writer shares with many others a natural pride in this notable achievement of American research, which has attracted attention by reason both of the large scale of its operations and of its thorough and painstaking execution. With the conclusions concerning the figure of the earth this paper is not especially concerned. It is with reference to Hayford's theoretical deductions within the realm of geophysics and geology upon the basis of Pratt's hypothesis of compensation that the writer would offer suggestions, particularly concerning the fundamental assumptions of which no account is taken in Hayford's papers. In his later article in *Science*—a presidential address—geologists are informed by Dr. Hayford that they have no recourse but to accept his conclusion. We quote:

> Within the past ten years geodetic observations have furnished positive proof that a close approximation to the condition called isostasy exists in the earth and comparatively near the surface [p. 199].
>
> The geodetic observations show that the isostatic compensation under the United States is nearly complete. It is not merely a compensation of the continent as a whole, it is a compensation of the separate, large, topographic features of the continent [p. 200].
>
> The compensation may properly be characterized as departing from completeness only one-tenth on an average [p. 201].

Elsewhere in the article over- or under-compensation is stated not to exceed that of a mass of rock strata 250 feet in thickness, on an average, and that the limiting depth of compensation is 122 km. (76 miles).

Printing Office, 1905), pp. 535–40; "The geodetic Evidence of Isostasy," *Proc. Wash. Acad. Sci.*, VIII (1906), 25–40; "The Earth a Failing Structure," *Bull. Phil. Soc. Wash.*, XV (1907), 57–74; "The Figure of the Earth and Isostasy from Measurements in the United States," *Dept. Com. and Labor, Coast and Geod. Surv.* (Washington, 1909), pp. 1–178, maps; "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," *ibid.* (Washington, 1910), pp. 1–80, maps; (with William Bowie) "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," *ibid.*, Special Publication No. 10 (1912), pp. 1–132, maps; William Bowie, "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (2d paper), *ibid.*, Special Publication No. 12 (1912), pp. 1–28, maps; "The Relations of Isostasy to Geodosy, Geophysics, and Geology," Science, XXXIII (1911), 199–208; "Isostasy, Rejoinder to the Article by Harmon Lewis," *Jour. Geol.*, XX (1912), 562–78. An outline of Hayford's studies from a very sympathetic standpoint is G. K. Gilbert's "Interpretation of Anomalies of Gravity," *Prof. Paper No.* 85 *C, U.S. Geol. Surv.*, 1913, pp. 29–37, Pl. 4.

Hayford's categorical statements reach their culmination in the following:

> These are the facts, established by abundant geodetic evidence. These facts may not be removed or altered by showing that difficulties are encountered when one attempts to make them fit existing theories, geological or otherwise. The theories must be tested by the facts and modified if necessary [p. 201].

Methods and assumptions within the field of the exact sciences.—Inasmuch as Dr. Hayford's statement last cited raises a question concerning the comparative reliability of the data obtained from geodetic and from geological observations, it may perhaps be pointed out that geologists have before been warned of the fallacy of their conclusions by workers in the field of the so-called exact sciences. Two fairly recent instances will suffice, though it would be easy to cite others.

With a degree of assurance which was perhaps warranted by his pre-eminence in research, the late Lord Kelvin served notice upon geologists that the longest period that could by any possibility be allowed them as representing time since the beginning of life upon the globe was a hundred million years, with a probability that it could not exceed twenty million years;[1] and this figure was soon reduced by Professor Tait to ten million years.[2] With the question of whether this allowance is adequate we are not at the moment concerned, since the developments in the realm of physics have destroyed the value of Kelvin's argument. At the meeting of the British Association held at Winnipeg in 1909, Sir J. J. Thomson, referring in his presidential address before that body to studies of radium by Rutherford and others, showed how Kelvin's argument was based upon incomplete evidence and must now be abandoned in view of the new light which has been shed upon the problem.[3]

It was Helmholtz, another conspicuous champion of the exact sciences, who stated that the atmospheric envelope of the earth could not extend above an altitude of 27 or 28 km., since the temperature gradient required that the absolute zero of temperature

[1] Sir William Thomson, "The Age of the Earth," annual address to Victoria Institute, *Phil. Mag.*, 1899, p. 66; also, *Popular Lectures and Addresses*, II, 64.

[2] *Recent Advances in Physical Science*, p. 174. See rejoinder by A. Geikie, *Landscape in History and other Essays* (1905), pp. 206–8.

[3] *Rept. Brit. Ass'n Adv. Sci., Winnipeg Meeting, 1909* (1910), pp. 27–28.

should be reached at that level.[1] From actual sounding of the atmosphere we now know that the convective zone within which the temperature gradient is essentially adiabatic ends abruptly at an altitude ranging from 9 to 18 km., and that the envelope extends to at least 70 km.,[2] with nearly isothermal conditions above the convective zone.

From these examples and others which might be cited, we should learn that while the methods of "exact science" may not be lacking in precision, the assumptions which enter into the solutions, whether they are used consciously or not, possess the same measure of fallibility as those employed in other fields of science. It is therefore with assumptions unconsciously made by advocates of isostatic compensation that this paper will deal.

Hayford's negative argument for a failing earth, based upon data now shown to be inapplicable.—In his paper entitled "The Earth a Failing Structure," Hayford has shown us how his conclusions and those of the late Sir George Darwin dealing with the same subject are diametrically opposed to each other, for the reason that the basal assumptions differ so widely. In the same paper six negative reasons are given why the earth must be a failing structure; that is, be incapable of supporting its protuberances by virtue of its rigidity. These reasons may be reduced to one and stated in this form: Even if the earth throughout had the strength of granite, it would upon the basis of known tests be incapable of supporting without failure the loads upon it. Since this statement was made, studies by Bridgman[3] and Adams[4] have shown that under hydrostatic conditions of compression such as must be conceived to exist within the earth the crushing strengths of materials are enormously enhanced over those derived from tests in which no lateral constraint is imposed—the data employed by Hayford. The studies

[1] Cf. A. Wegener, *Thermodynamik der Atmosphäre* (1911), pp. 109, 185.

[2] W. S. Bruce, *Polar Exploration* (London, 1911), pp. 210–11.

[3] P. W. Bridgman, "The Collapse of Thick Cylinders under hydrostatic Pressure," *Physical Review*, XXXIV (January, 1912), 1–24.

[4] F. D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (February–March, 1912), 97–118. See also L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior, *ibid.*, pp. 119–38.

by Bridgman were made upon hollow metal cylinders, while Adams has interpreted his results to show that the crushing strength of granite is at least seven fold as great as has been supposed. Test blocks of Westerly (Rhode Island) granite at ordinary temperatures first began to flow with pressures of 200,000 pounds to the square inch. In a discussion of these results King says:

> No state of shearing stress in the crust of the earth due to the weights of continents and mountains can cause the collapse of the rock in the neighborhood of a small cavity. . . . . At a temperature of 550° C. supposed to exist eleven miles below the earth's surface cavities will remain open when submitted to considerably greater pressures than are found at this depth.[1]

Though applying to forces whose continuance of application is short (six hours), many lines of evidence confirm the assumption of the great rigidity of the earth's crust—much the most exact as well as the most recent being the determination by Michelson that in this respect it exceeds solid steel.[2]

Recent unpublished experiments by Bridgman have an important bearing upon this point. I am permitted to quote the following from a personal letter:

> I have recently made a few experiments which show that at least for some substances the viscosity increases enormously with increasing pressure. The effect may certainly be as great as two hundred times for an increase of 1,000 atmospheres, and increases at least as rapidly as the square of the pressure.

Hayford's negative argument in favor of isostasy has thus upon the basis of later work been shown to be fallacious. In his official monographs he has supplied what he considers conclusive positive evidence in support of his contention that isostatic compensation is nearly perfect at a depth of 76 miles below sea-level—in other words, that elevations above the surface persist only by virtue of a deficiency of mass, and that basins are situated above a basement of exceptional density. Upon his hypothesis the quantity of matter is the same in all vertical columns of the same cross-section and limited below at the assumed depth below sea-level of 76 miles. This "positive" argument rests, however, upon Pratt's hypothesis, and implies a weak and failing earth shell.

[1] *Op. cit.*, p. 137.

[2] A. A. Michelson, "Preliminary Results of Measurements of the Rigidity of the Earth," *Jour. Geol.*, XXII (1914), 97–130.

His positive argument and the facts upon which it is based.—Hayford's earlier studies have dealt with the well-known differences between the astronomic and the geodetic determinations of latitude, longitude, and azimuth—so-called deflections of the vertical—measured first at 267 stations, and in a supplementary study at 116 stations, making in all 383, which are fairly well distributed over the domain of the United States. These uncorrected residuals have values which when expressed in terms of astronomic minus geodetic determination (A–G) range between $-26''.50$ and $+32''.43$, the average being, however, comparatively small. The later monographs have dealt with pendulum determinations of gravity, made at 89 stations in the first study and 35[1] in the second, a total of 124. Unfortunately, instead of correcting the measurements of gravity so as to take account of both altitude and topography and obtain a comparison of observed and computed values, Hayford has combined with the correction for topography one for "compensation" with reference to the assumed limiting surface at a depth of 76 miles below sea-level. Fact and theory have thus been combined in his tables in such a way as to make it impossible to extricate the figures representing the anomalies of gravity at each station *except upon the Pratt-Hayford hypothesis.* We are thus thrown back upon those earlier studies which deal with deflection of the vertical.

HAYFORD'S FUNDAMENTAL ASSUMPTION CONCERNING THE DISTRIBUTION OF MASS WITHIN THE EARTH'S SURFACE-SHELL

Lack of knowledge concerning distribution of mass beneath the earth's surface.—If we assume, as Hayford has done in conformity with the usual conception, that the differences between geodetic and astronomic locations of station are a measure of the horizontal components of the earth's gravitation at the station, these differences must be assumed to be made up of the horizontal components of the pulls from all elementary volumes of the earth when multiplied by mass and divided by the square of the distance from the station. But next to nothing is known concerning the distribution of density within the lithosphere. As Gilbert has said, "The inner earth is the inalienable playground of the imagination."

[1] By Bowie alone.

Preponderant effect of near masses due to law of inverse squares.—It is a direct consequence of the law of inverse squares that bodies relatively near the station exert a preponderant influence upon the intensity of gravity, and a relatively small mass of high density within a few miles of the station may thus be responsible for the major portion of the anomaly in the direction or intensity of gravity. To employ an illustration from the field about a magnetic needle: the local variation in the pointing of the needle may be explained either, upon the one hand, by the location of the station with reference to the magnetic poles of the earth, or, upon the other, by the propinquity of excessively magnetic masses—such, for example, as a deposit of magnetic iron ore. Within the Mississippi plain we find generally "normal" conditions explainable by the position of stations with reference to magnetic poles; whereas in many areas of the northern peninsula of Michigan the notable magnetic "anomaly" is explainable almost entirely by local conditions.

It has sometimes been claimed that the extension of Clairaut's theorem by Stokes makes the value of Δg. independent of local (that is, near-by) variations in density, which may be both large and abrupt. This, however, is not the case. The non-permissibility of such variations for the application of the theorem was recognized by Stokes[1], as it has been by Rudzki.[2] Clairaut in fact developed the theorem to apply to an earth supposed to have a liquid interior.

Hayford's explanation of anomalies found in systematic regularity as contrasted with local irregularity in distribution of mass.—Hayford's studies of the deflection of the vertical and of gravity irregularities within the United States have been carried out upon the assumption that they are explainable by general, as contrasted with local, conditions; and his method of reducing residuals falls in with the explanation of magnetic variation within the Mississippi plain. A solution of the problem of anomalies in the intensity of terrestrial magnetism in northern Michigan which caused these residuals to disappear through a process of general averaging would constitute a proof, not of the certitude of the hypothesis assumed, but rather of its falsity.

[1] *Mathematical and Physical Papers*, II, 164.

[2] *Physik der Erde*, pp. 35–36.

The earth's density as a whole being more than double that of the part known to us from observation, we may assume almost any distribution of matter which arranges the concentric shells in inverse order of density from the center to the surface. It is in fact quite as probable that near the surface contacts between successive shells of different density are abrupt as it is that they are gradual. Hayford has assumed, though he does not appear to regard it as an assumption of importance, that down to a depth of 76 miles (122 km.)[1] no shell of notably higher density than that at the surface is encountered. It is, however, entirely within the realm of probability that material in all respects resembling the stone meteorites or stone-iron meteorites may be found within this depth. If, further, the surface of contact between a lower shell of higher density and a higher shell of lower density is not only abrupt but irregular and characterized by notable local prominences, an explanation can be found for most local anomalies of gravity.

EVIDENCE OF LOCAL IRREGULARITIES IN DISTRIBUTION OF GRAVITY AND MAGNETIC CONSTANTS

Evidence from Russia and from Southern Italy.—It is proposed now to state certain evidences that local conditions may be responsible for large anomalies in the value of gravity. The evidence now upon record has been drawn from a number of widely separated provinces, in all of which extended series of measurements either of gravity or of deflection of the plumb line have been carried out.[2] The great plain of Russia is of special interest in a discussion of isostasy, since any anomalies in gravity which occur do not require

[1] Helmert has distinctly recognized that there are anomalies of gravity not explainable on general conditions, but, using the same assumption of the truth of Pratt's hypothesis, he has determined the depth of the *Ausgleichfläche* to be 118±22 km. He has chosen for this purpose the zones of special disturbance above and on either side of the steep slope bordering the continental shelves (F. R. Helmert, "Die Tiefe der Ausgleichfläche der Prattschen Hypothese für das Gleichgewicht der Erdkruste und den Verlauf der Schwerestörung vom Innern der Kontinente und Ozeane nach den Küsten," *Sitzungsber. d. k. preusz. Akad. d. Siss. z. Berlin*, 1909, pp. 1192–98).

[2] F. de Montessus de Ballore, "Sur les anomalies de la pésanteur dans certains régions instables," *Comptes Rendus de l'Académie Française*, CXXXVI (Paris, 1903), 705–7.

large corrections for topography. It has been found, however, that in the great triangle Kamiensk-Podolsk, Kazan, Astrakhan, which relatively to the surrounding country is very unstable in a seismic sense and is bordered by dislocations, the measurements of gravity made by General Stebnitzki[1] have shown a notable deficit of gravity to characterize this marginal zone. A like threefold correspondence of seismic instability, of zones of dislocation, and of abnormal gravity has been proved for a number of other regions, notably Southern Italy and Sicily,[2] the Indo-Gangetic plain to the southward of the great protuberance of the Himalayan Highland, the North German plain, and a district in Hungary.

Evidence from India.—As the Russian province is of interest because the topographic correction is small, so the Indo-Gangetic plain at the southern base of the Himalayas offers a contrasted set of conditions and presents the best possible opportunity for testing the influence upon deflection constants of a huge protuberance of the lithosphere whose volume and probable density may be subjected to computation. It is thus of interest to find that Colonel Burrard[3] is led to ascribe the deficit of gravity in the Indo-Gangetic plain to the known zone of dislocation in correspondence with the zone of seismic instability; his view being that a great rift in the *subcrust* filled with material of low density extends to considerable depths beneath this zone.

Colonel Burrard is exceedingly favorable to the Pratt-Hayford conception of isostasy and has made computations based upon Hayford's earliest figures for the surface of compensation, yet he does not find that the residuals are thereby decreased, but, on the contrary, that they are enhanced. For the entire distance of 25 miles separating Kurseong in the outer Himalayas and Jalpaiguri

[1] M. A. de Lapparent, "Sur la signification géologique des anomalies de la gravité," *ibid.*, CXXXVII (1903), 827–31.

[2] Annibale Riccò, "Determinatione della gravità relativa in 43 luoghi della Sicilia orientale, della eolie, e della Calabria," *Mem. della Soc. degli spettroscopisti Italiani*, XXXII (1903), 173–296.

[3] Col. S. G. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India* (Calcutta, 1912), pp. 1–26. See also by the same author, "The Origin of Mountains," *Geol. Mag.*, Dec. V, Vol. X (1913), pp. 385–88; and "On the Origin of the Indo-Gangetic Trough, Commonly Called the Himalayan Foredeep," *Proc. Roy. Soc.*, A, XCI (1915), 220–38.

upon the plains, the difference in deflection is 45″, instead of 26″, which it should either equal or exceed on the conception of support by rigidity without compensation, and 15″, as it must be according to Hayford's hypothesis.[1] In a separate monograph of the Indian Survey, Major Crosthwait has discussed the application of Hayford's theory to the Himalayan area and has found that whereas for the United States as a whole the mean residual is 1″.86 and for all save the western section 1″.15, for the Himalayas it is more than eight times this amount.[2] Dr. Hayden has shown that to secure compensation the depth of the equilibrium surface must be increased from Hayford's figure of 122 km. to 330 km.[3] Applied in the region where it is most crucially tested, the Hayford hypothesis thus receives less support in the facts than does the doctrine of non-compensation.[4]

Mutual relationships of abnormal gravity, abnormal earth magnetism, dislocations, and seismicity.—In at least three widely separated provinces the coincidence of anomaly of terrestrial magnetism with that of gravity, and with that of dislocation zones, has been proved by the data from official surveys. In the earthquake province of Calabria and Sicily this result has been reached by a Royal Commission under the direction of Professor Riccò.[5]

A close correspondence between anomaly of gravity and that of terrestrial magnetism has likewise been brought out to special advantage within a province in Hungary which is relatively small, but one provided with an especially large number of stations, so

[1] Burrard, *op. cit.*, p. 4. See also Sir Thomas Holland, "The Origin of the Himalayan Folding," *Geol. Mag.*, Dec. V, Vol. X (1913), pp. 167–76.

[2] Major H. L. Crosthwait, R. E., "Investigation of the Theory of Isostasy in India," *Prof. Paper No. 13, Survey of India* (Dehra Dun, 1912), pp. 1–123.

[3] H. Hayden, "Notes on the Relationship of the Himalaya to the Indo-Gangetic Plain," etc., *Geol. Surv. India*, XLIII (1913), 138–67, Pls. 3, 4.

[4] The stations discussed by Bowie from the Indian district to indicate harmony with the Hayford doctrine are far removed from the Himalayas (W. Bowie, "Isostasy in India," *Jour. Wash. Acad. Sci.*, IV [1914], 245–49.)

[5] A. Riccò, "Anomalie del magnetismo terrestre in relatione alle anomalie della gravità nella Sicilia orientale," *Boll. dell' Accad. Gioenea di Scienze Naturali in Catania*, Fasc. 80 (1904), pp. 1–3. See also "Anomalie della gravità e del magnetismo terrestre in Calabria e Sicilia," *Annali dell Ufficio Centrale Meteorologico e Geodinamico Italiano*, XIX (1897; separate printed at Rome in 1907), 1–10, plate; also, "Anomalie della gravità e del magnetismo terrestre in Calabria e Sicilia in relatione alla costituzione del suelo, *Boll. della Soc. Sism. Ital.*, XII (1907), 393–407.

that the lines of equal anomaly of gravity have been drawn for each millimeter of acceleration.[1] The sharp changes—steep gradients—upon the map thus come into prominence, and these show very close correspondence with strong abnormality of the magnetic forces and with the intensity of earthquakes, the seismicity of the province having been investigated by Rethly.[2]

For the area of the North German plain, Deecke, making use of data upon magnetic constants determined by Schück and of those of gravity issued by Helmert from the Royal Prussian Geodetic Institute at Potsdam, has shown that the lines of equal anomaly of gravity correspond closely with those of terrestrial magnetism (involving both inclination and declination), and that these lines are further, in many cases, those of recent faulting, and in some cases were probably the seats of movement during the earthquake of October 23, 1904.[3] In this connection it is of interest that a resurvey of magnetic elements in Japan subsequent to the great earthquake of 1891 indicated remarkable changes in the isomagnetics of the province.[4]

In connection with a general survey of geodetic data assembled from many regions, Helmert, though approving Hayford's views, has concluded that gravity values are in many localities not completely in harmony with Pratt's hypothesis,[5] and that this is especially true for the oceanic islands, for the margins of the continental

[1] Baron Roland Eötvös, "Bestimmung der Gradienten der Schwerkraft und ihrer Niveauflächen mit Hülfe der Drehwage," *Abh. der XV. Allgemeinen Konferenz der Erdmessung in Budapest, 1906*, I, 1–59 (reprint). See also, by the same author, "Über Arbeiten mit der Drehwage ausgeführt im Auftrage der königlichen ungarischen Regierung in den Jahren 1909–1911," *Bericht an die XVII. Allgemeine Konferenz der Internationalen Erdmessung* (Budapest, 1912), pp. 1–17.

[2] *Földrajzi Közlemenyek*, XXXIX, 391–420.

[3] W. Deecke, "Erdmagnetismus und Schwere in ihrem Zusammenhange mit dem geologischen Bau von Pommern and dessen Nachbargebieten," *Neues Jahrb. f. Mineral.*, etc., Beilage Bd. 22 (1906), pp. 114–38, Pls. 1–3.

[4] D. Kikuchi, *Jour. Coll. Sci. Univ. Tokyo*, V, 149–92.

[5] Wenn Pratts Hypothese erfüllt ist, so müssen sich die Schwerestörungen Δg. lediglich aus Höhenstörungen der Massenlagerung über der Ausgleichsfläche erklären lassen. Dies gelingt aber nicht völlig; man muss daher auch noch Horizontalverschiebungen annehmen, welche die Massenlagerung gestört haben. Es treten sogar ausgedehnte Massenstörungen auf, wo die sich gegenseitig ausgleichenden Massen nicht erkennbar sind, so dass man nur schlechthin von Anhaüfungen und Defekten sprechen kann, die sich also als erhebliche Abweichungen von Pratts Hypothese darstellen" (*Sitzungsber. Berliner Akad. d. Wiss.* [II, 1908], 1060).

shelves, for mountain summits, and for intermontane valleys. He gives, as the most noteworthy of aberrant districts, Hawaii, Corsica, Sicily and Calabria, the Austrian Alps and the Carpathians, large areas in Turkestan continued eastward to the Pamirs, Lake Baikal, and localities within the valley of the Obi River in Siberia. These, with the exception of the one last mentioned, from which few seismic data are available, are notably the great earthquake zones of the Eastern Hemisphere.[1]

HAYFORD'S FIGURES ANALYZED WITH THE IDEA OF COMPENSATION ELIMINATED

Deflections corrected for topography to find attraction of hidden masses.—We have thus seen that in many regions the evidence favors the view that anomaly of gravity is connected with local irregularity and not alone with general and orderly—systematic—distribution of mass over a wide area. Hayford's gratuitous assumption has been that the distribution of mass which produces gravity anomaly (Δg.) is throughout regular and systematic; and to this he has added the additional assumption of a failing earth, which in the light of recent work does not appear to be well founded. Pratt's hypothesis of compensation was designed to meet conditions within an earth shell of supposed high plasticity, and Hayford has contributed to this theory a determination of the supposed depth of the compensation surface. His assumed proof has consisted in testing by the method of least squares a number of hypothetical *systematic* distributions of matter in the unknown region, with the use of the measurements of deflection of the vertical and of gravity within the area of the United States. His choice of the depth of 76 miles for complete compensation was based upon a reduction of the sum of the squares of the residuals to about one-tenth of that obtained upon the hypothesis of a rigid earth *without important local irregularities in distribution of matter.*

If it be true that local anomaly is to be ascribed largely to irregular local distribution of mass beneath and near the station, Hayford's method is inapplicable and can only lead to erroneous results.

[1] Cf. de Montessus, "Les tremblements de Terre," *Géographie Seismologique* (Paris, 1906), Map 1.

Let us then see from examination of his figures whether they betray evidence of large local as against broad systematic distribution only of the concealed matter beneath and about the station. For reasons already given, this test of his figures is possible only in case of the deflections of the vertical.

Distribution of residuals in excess of 50″ of arc.—Hayford has computed with considerable care the topographic deflections for each station, and this resultant horizontal pull of the *determinable* masses at the station, when deducted from the measured deflection, must leave a residual fixed by the *hidden* masses whose distribution of density is unknown. By assembling his topographic corrections and applying them we obtain residual deflections which range from zero to 89″.46 of arc.[1] We have arbitrarily selected in a first survey of the results an arc of 50″, or something more than half the maximum residual, as a *minimum of excessive anomaly* in order to determine the plan of distribution. The results are shown in Table I.

Thus it is seen that 100 stations out of a total of 774 (numbering stations separately for latitude and for longitude or azimuth) gave residuals, after correction for known distribution of matter, which are in excess of 50″ of arc. These constitute 12.9 per cent, or about one-eighth of the entire number, and it is a fact of much significance that, with the exception of two stations which are

[1] We may here ignore the sign of the residual deflection, which indicates the direction of displacement of the zenith. The topographic correction is for the coastal regions particularly large and often several times the measured deflection. It is therefore interesting to find that the uncorrected deflections are also in the Pacific coastal region the largest for the United States. Deflections of the vertical for the entire series of Hayford which are in excess of 15″ are the following, with station numbers given:

In meridian: 238, Santa Barbara (−18.38); 245, Los Angeles (−17.99); 364, Mt. Wilson (−28.50).

Prime vertical: 1, Point Arenas (+16.98); 224, Tepusquet (+20.15); 225, Arguello (+15.90); 227, New San Miguel (+20.62); 228, Santa Cruz W. (+19.71); 229, Santa Barbara (+15.04); 230, Los Angeles N.W. (+19.56); 231, Los Angeles S.E. (+21.55); 236, Sulphur Pk. (+18.82); 237, Ross Mt. (+18.18); 241, Avila (+29.93); 242, San Buenaventura (+19.38); 244, Soledad (+28.06); 245, San Diego (+32.43); 23, Genoa (−18.65); 42, Ogden (+16.25); 43, Waddoup (+24.84); 44, Salt Lake City, Long. Sta. (+15.37); 45, Salt Lake City, Az. Sta. (+18.15); 46, Mt. Nebo (+18.69); 61, Colorado Springs (−18.74).

TABLE I

"ABNORMAL" DEFLECTIONS OF THE VERTICAL—HAYFORD (CORRECTED FOR TOPOGRAPHY)

(Minimum, 50″ of Arc)

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN MERIDIAN			
233	Mt. Toro	36°32′	121°37′	52″34
234	Arguello	34 35	120 34	53.97
236	Santa Cruz W	34 4	119 55	56.62
237	New San Miguel	34 2	120 23	55.30
242	Lospe	34 54	120 36	51.08
246	Dominguez Hill	32 52	118 14	59.03
254	Point Pinos	36 38	121 56	51.00
260	San Luis Obispo	35 11	120 45	52.41
261	Avila	35 11	120 43	50.22
264	San Buenaventura	34 16	119 16	53.29
265	San Pedro	33 43	118 17	58.61
266	Santa Catalina	33 26	118 30	57.90
267	Soledad	32 50	117 15	50.04
361	Harbor	33	118 34	54.22
362	Wilson Peak	34 13	118 3	50.50
363	Los Angeles N.W	33 55	118 3	53.98
	DEFLECTIONS IN PRIME VERTICAL (LONGITUDE)			
1	Point Arena	38 55	123 41	87.65
3	Ukiah	39 9	123 12	81.84
6	New Presidio	37 48	122 27	79.47
7	Lafayette Park	37 48	122 26	80.34
8	Washington Square	37 48	122 25	80.26
9	Mt. Hamilton	37 21	121 38	77.84
10	Marysville	39 8	121 35	75.75
16	Sacramento	38 35	121 30	75.07
246	San Diego 1871	32 43	117 9	62.49
20	Lake Tahoe S.E.	38 57	119 57	70.88
22	Verdi	39 31	119 59	66.21
23	Genoa	39	119 51	71.66
24	Carson City	39 10	119 46	62.26
25	Virginia City	39 19	119 39	59.71
216	San Diego	32 43	117 9	63.69
217	Los Angeles Normal Sch. 001	34 3	118 15	61.52
243	Buenavista	34 3	118 15	61.26
352	Wilson Peak	34 13	118 3	61.22
353	Mare Island	38 6	122 16	75.54
361	Gazelle	41 32	122 31	75.50
367	Eugene	44 4	123 5	77.72
372	Portland	45 31	122 41	63.58
376	Tacoma	47 16	122 27	57.98
377	Seattle, 1908	47 40	122 19	57.79
378	Seattle, 1888	47 37	122 20	58.77
381	Port Townsend	48 7	122 45	60.71
382	Blaine	48 59	122 45	50.95

TABLE I—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)			
2	Paxton	39° 8′	123° 19′	78.″79
4	Mt. Helena	38 40	122 38	66.59
5	Mt. Tamalpais	37 55	122 36	77.95
224	Tepusquet	34 55	120 11	60.63
225	Arguello	34 35	120 34	70.19
226	Gaviota	34 30	120 12	63.38
227	New San Miguel	34 2	120 23	59.65
228	Santa Cruz W	34 4	119 55	56.70
229	Santa Barbara	34 24	119 43	58.71
234	Dominguez Hill	33 52	118 14	58.01
236	Sulphur Peak	38 46	122 51	66.37
237	Ross Mountain	38 30	123 7	72.48
238	Point Avisadero	37 44	122 22	88.84
239	Monterey Bay	36 36	121 53	89.46
240	Santa Cruz	36 59	122 3	73.20
241	Avila	35 11	120 43	54.51
242	San Buenaventura	34 16	119 16	52.56
221	Santa Lucia	36 9	121 25	81.74
222	Castle Mount	35 56	120 20	65.75
223	Lospe	34 54	120 36	71.71
11	Monticello	38 40	122 11	72.19
12	Vaca	38 23	122 5	74.89
13	Mt. Diablo	37 53	121 55	75.38
14	Yolo, N.W. Base	38 41	121 51	68.34
15	Yolo, S.E. Base	38 32	121 48	69.97
17	Mocho	37 29	121 33	77.15
18	Mt. Lola	39 26	120 22	75.44
19	Round Top	38 40	120	74.44
21	Lake Tahoe S.E.	38 58	119 57	63.96
26	Mt. Conness	37 58	119 19	66.91
27	Carson Sink	39 35	118 14	60.49
218	Santa Ana	36 54	121 14	72.64
219	Mt. Toro	36 32	121 37	78.97
220	Hepsedam	36 19	120 49	65.71
111	Cape Henry Lighthouse (old)	36 56	76 1	52.72
116	Wolftrap	37 24	76 15	51.02
351	Harbor	33	118 34	72.60
354	Snow Mountain E.	39 23	122 45	81.50
355	Marysville Butte	39 12	121 49	82.51
356	Mt. Grant	38 34	118 47	61.80
357	Kent	39 58	122 44	81.52
358	Lyons	40 18	121 38	77.35
359	Round	40 48	121 57	77.95
362	Rust	42 37	122 21	75.06
363	Onion	42 41	123 14	85.05
364	Scott	43 22	123 4	85.76
365	Spencer	43 59	123 6	81.06
368	Mary	44 30	123 33	76.64
369	Yam	45 4	123 9	76.15
370	Barnes	45 32	122 45	63.31

TABLE I—*Continued*

DEELECTIONS IN PRIME VERTICAL (AZIMUTH)—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
371......	Balch......................	45°32′	122°43′	63″.70
373......	Lam.......................	46 8	122 28	68.56
374......	Bel........................	46 47	121 56	59.78
379......	Point Hudson..............	48 7	122 45	66.69
389......	Classet....................	48 23	124 40	52.32
390......	Beechy Head...............	48 20	123 39	56.69

located in the Atlantic Coast province (see below, p. 711), all are to be found within the intense seismic area of the Pacific coastal region, which was so recently, after the destructive California earthquake of 1906, the subject of special investigation. When now the stations showing notable anomaly are accurately plotted upon the special map of the seismic province prepared by the Earthquake Investigation Committee,[1] it at once appears that there is an apparent relationship between their distribution and that of the better-known recent faults of the province. The number of stations with corrected anomaly of deflection greater than 50″ is something more than half (58 per cent) of the total number of stations within the Pacific Coast province. In the map of Fig. 1 which shows the distribution of the abnormal stations (in dotted outlines the map of the Earthquake Investigation Committee) black circles of different diameters have been used to bring out roughly the magnitude of the corrected residuals, and it appears that those of higher order particularly are generally grouped near the known displacements of the district, some of which have been the seats of movement during recent earthquakes.[2]

Distribution of residuals in excess of 35″ of arc.—Had the minimum of abnormality of deflection been made 35″ of arc, instead of

[1] A. C. Lawson, G. K. Gilbert, H. F. Reid, J. C. Branner, A. O. Leuschner, George Davidson, Charles Burckhalter, and W. W. Campbell, *Atlas of Maps and Seismograms* accompanying the *Report of the State Earthquake Investigation Committee upon the California Earthquake of April 18, 1906* (Carnegie Institution of Washington, 1908), Map 1.

[2] The recent faults are not indicated on the area outside the dotted border. Few gravity data relatively are available for the area east of California, where many fault lines are shown.

50", practically all of the remaining stations located within the California earthquake province would have been included, and a separate group would have been found within the Atlantic coastal

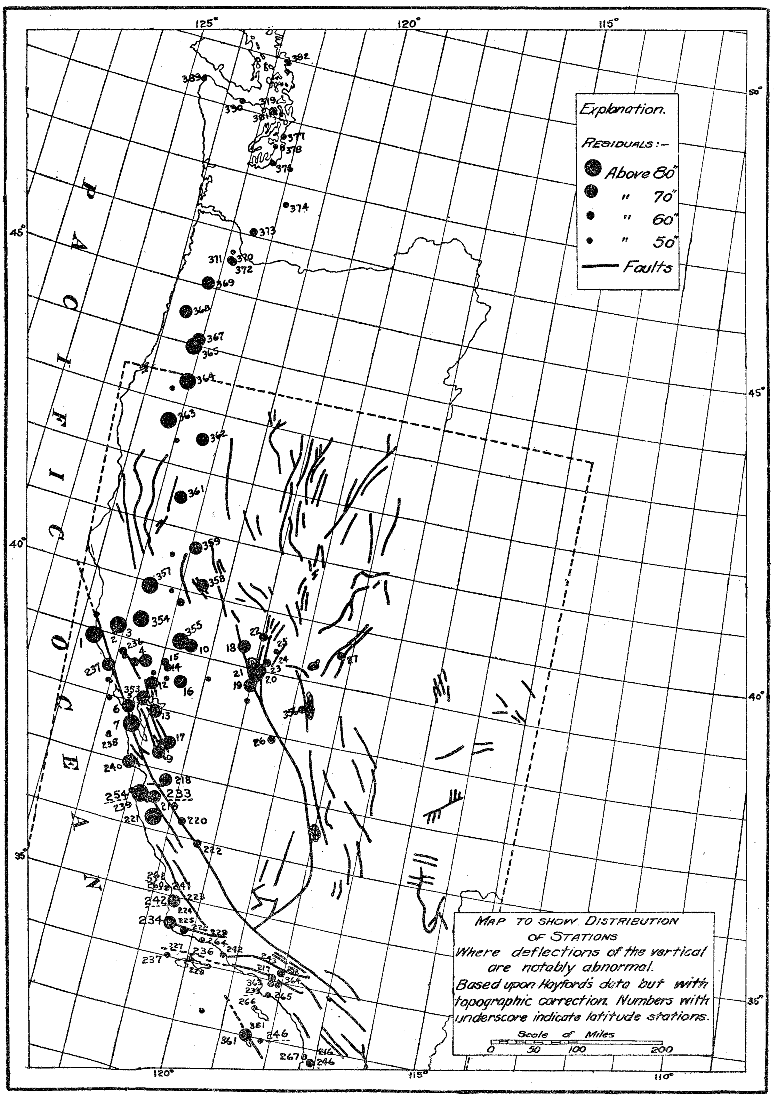

FIG. 1

province (Hayford's northeastern and southeastern groups of stations). This supplementary list prepared upon the basis of a minimum of abnormality of 35″ of arc, but without including the additional Pacific slope stations, is given in Table II, following.

The stations listed in this table have been plotted and appear in the map of Fig. 2 with some indication of the measure of abnormality, and upon the map of Fig. 3 are found the points of higher seismicity as determined by De Montessus upon the basis of recorded data,[1] which, however, of necessity give undue prominence to localities of early settlement or of later importance commercially.

General conclusion as to law of distribution of anomaly of gravity.— Hayford's own observations thus confirm the evidence derived from other regions that anomaly of deflection of the vertical and of gravity show large local defect or excess, and that these local anomalies are in some way connected with the distribution of seismicity and with zones of dislocation.[2] We believe therefore that the late Professor de Lapparent was correct when in 1903 he stated with much force before the French Academy:

> I believe, therefore, that for the present we may claim that the sea upon the one hand, and the continents upon the other, enter into the variations of gravity there only where a dislocation puts into contact two crustal compartments, one of which is depressed and one of which remains stationary or is fixed. . . . .
>
> One may add that even in countries where the surface does not reveal the dislocations, a means is found for diagnosing the deep and hidden faults. Finally, the relation of seismic regions to rapid variations in the anomaly of gravity shows that it would be eminently proper to carry out such studies in order to make known those provinces of our globe which have most to reckon with the danger from earthquakes [translation].[3]

May not the truth, as in so many other controverted questions, lie between the extreme viewpoints? It is possible to assume

[1] Count F. de Montessus de Ballore, "Les Etats Unis séismiques," *Archives des Sciences Physiques et Naturelles de Génève*, 4th period, V (1898), 201–16. See also William H. Hobbs, "On Some Principles of Seismic Geology," *Gerlands Beiträge zur Geophysik*, VIII (1907), Appendix, pp. 289–92, Pl. 2; also, *Earthquakes* (Appleton, 1907), pp. 112–16.

[2] While magnetic data are available for the territory of the United States (*United States Magnetic Tables and Magnetic Charts for 1905* [Washington, 1908]), their discussion by Bauer is still unpublished, and it would be premature to discuss them here.

[3] M. A. de Lapparent, *op. cit.*, pp. 830–31.

TABLE II

"ABNORMAL" DEFLECTIONS OF THE VERTICAL—HAYFORD (CORRECTED FOR TOPOGRAPHY) (MINIMUM, 35″ OF ARC)

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN MERIDIAN			
136......	Yard......................	39°58′	75°23′	37″.81
137......	Mt. Rose....	40 22	74 43	35.22
158......	Howard....................	44 38	67 24	37.97
164......	Calais.....................	45 11	67 17	35.97
350......	Folger.....................	41 17	70 6	38.56
	DEFLECTIONS IN PRIME VERTICAL (LONGITUDE)			
90......	Charlottesville..............	38 2	78 31	43.20
92......	Strasburg..................	38 59	78 22	38.42
99......	Naval Observatory..........	38 55	77 4	37.40
100......	Naval Observatory..........	38 54	77 3	38.28
101......	C. and G.S. Observatory.....	38 53	77 1	35.61
108......	Dover.....................	39 9	75 31	38.69
110......	Cape May..................	38 56	74 56	44.91
113......	Roslyn....................	37 14	77 24	40.74
114......	Staunton..................	38 9	79 4	39.74
118......	Seaton....................	38 53	77	35.51
119......	Statesville.................	35 47	80 54	36.38
157......	Cambridge................	42 23	71 8	41.42
158......	Duxbury..................	42 3	70 40	42.19
172......	Bangor....................	44 48	68 47	35.14
173......	Calais.....................	45 11	67 17	35.92
233......	Provincetown..............	42 3	70 11	39.05
253......	Kit........................	41 30	73 59	41.63
257......	Mt. Weather...............	39 4	77 53	44.77
	DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)			
91......	Clark.....................	38 19	78	41.78
93......	Long Mount...............	37 17	79 5	44.99
94......	Bull Run..................	38 53	77 42	40.30
95......	Maryland Heights..........	39 20	77 43	41.52
96......	Sugarloaf..................	39 16	77 24	42.61
97......	Causten...................	38 56	77 4	35.32
109......	Cape Henlopen.............	38 47	75 5	46.63
111......	Cape Henry................	36 56	76 1	52.72
115......	Knott Island, North End.....	36 34	75 55	47.68
116......	Wolftrap..................	37 24	76 15	51.02
117......	Tangier Island..............	37 48	75 59	42.32
120......	Moore.....................	36 24	80 17	37.72
122......	King......................	35 12	81 19	35.29
142......	Yard......................	39 58	75 23	42.26
143......	Mt. Rose..................	40 22	74 43	46.12
144......	Beacon Hill................	40 22	74 14	42.50
147......	Cambridge................	42 23	71 8	38.24

TABLE II—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN PRIME VERTICAL (ASIMUTH)—*Continued*			
149......	Spencer....................	41°41′	71°30′	45.″30
150......	Beaconpole................	42	71 27	43.38
151......	Copecut....................	41 43	71 4	40.10
152......	Indian......................	41 26	70 41	46.49
153......	Shootflying................	41 41	70 21	37.97
154......	Blue Hill..................	42 13	71 7	41.90
156......	Thompson..................	42 37	70 44	40.35
159......	Unkonoonuc................	42 59	71 35	37.98
161......	Agamenticus...............	43 13	70 42	41.42
235......	Davis......................	38 20	75 6	48.87
248......	Mt. Blue...................	44 44	70 31	37.15
254......	Gardiners Island...........	41 6	72 6	37.42
255......	Barnegat Inlet.............	39 46	74 6	40.78
258......	Cahas......................	37 7	80 1	38.07
338......	Chapel Hill................	40 24	74 4	44.23
383......	Sankaty Head...............	41 17	69 58	37.71
384......	High Point.................	41 19	74 40	40.99
385......	Womelsdorf.................	40 19	76 12	40.98

that a tendency to attain to isostatic adjustment exists within the earth's outer shell as a consequence of diastrophic action, and that at any given time large areas, such as the greater portion of the United States, are measurably compensated. In areas more recently disturbed and at a more rapid rate (western section of the United States or the Himalaya region), which still betray their lack of stability in earthquakes, no such state of isostatic compensation can be postulated. Such regions show a rigidity sufficient to support their excessive loads for long periods even if measured in geological units, and if they yield to some extent through eventual fatigue of the materials under strain, this effect lags far behind the degrading effects of surface erosion and transportation. Some suggestion of this idea appears to be found in the paper by Crosthwait.[1]

CRITICISM OF HECKER'S DETERMINATIONS OF GRAVITY OVER THE OPEN SEA

Helmert's claim that gravity is nearly constant over deep water of the ocean.—A line of evidence which has been held to support the conception of isostatic compensation, but for the oceanic areas

[1] *Op. cit.*, pp. 4–5.

only, is that supplied by Helmert and Hecker, who have applied the Mohn hypsometer-barometer to measurements of gravity over the open sea. Upon the basis of these studies, which were executed

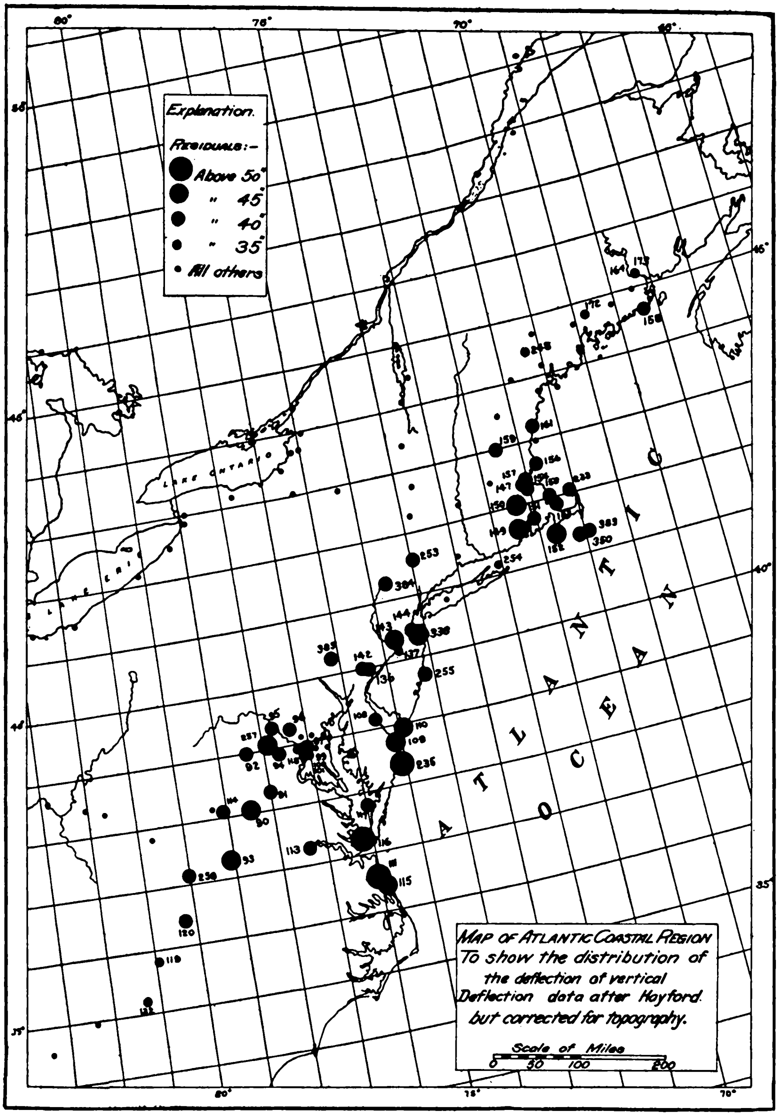

FIG. 2

by Hecker, Helmert has claimed that "the force of gravity above the deep water of the Atlantic Ocean between Lisbon and Bahia is nearly normal"—that is to say, the same as at the shore within

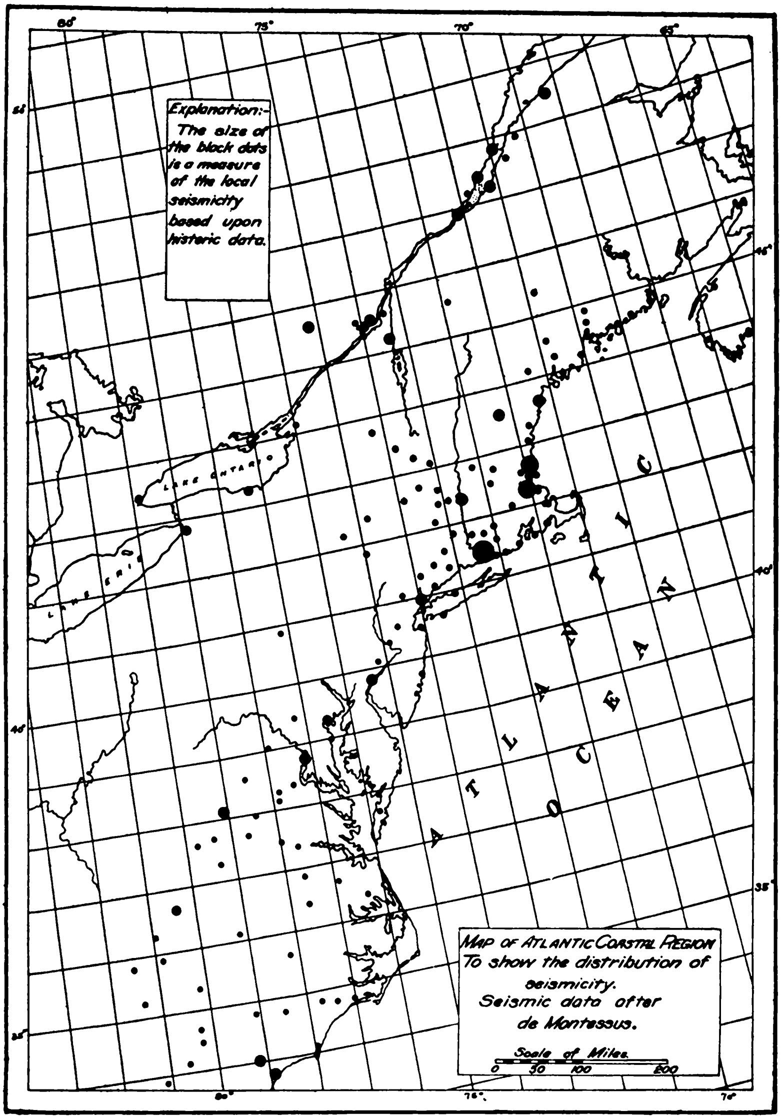

FIG. 3

the same latitude.[1] If this statement is well founded, it would be difficult to escape the conclusion that at least partial compensation exists for the oceanic areas. But from examination of the figures in Hecker's original monograph,[2] a different form of statement would seem better to express the facts. Up to the time of Hecker's Atlantic voyage geodesists, through basing their conclusions upon pendulum observations made upon a few oceanic islands, had held the belief that gravity is uniformly in excess over the oceans; and the force of Helmert's statement lay in the fact that it exploded this notion, which had received official sanction from an international geodetic congress. A better form of statement would appear to have been that Hecker's results did not in general reveal the high excess above normal values which had been expected. But values of Δg. which range from 146 units[3] of defect to 161 units of excess can hardly be called nearly constant unless errors of measurement be assumed to be excessive.

Hecker's grouping of his data objectionable in that it tends to efface significant local anomalies.—Hecker's paper is open to the objection that by a process of averaging the local significance of Δg. is made largely to disappear. Of this, two examples will suffice: the first, of measurements made over the shallow North Sea and British Channel with depths ranging from 60 to 160 meters only; and the second, a group of four measurements made between the Cape Verde Islands and the equatorial ridge over unknown but presumably large depths, which from a few not very distant soundings are probably generally in excess of 5,000 meters (Tables III and IV).

Hecker's revision of his data after the Black Sea cruise.—The figures as first published by Hecker were shown by Baron Eötvös to need correction for direction of motion of the vessel (west or east), and after having tested the magnitude of this correction in a special

[1] F. R. Helmert, "Dr. Heckers Bestimmung der Schwerkraft auf dem atlantischen Ozean," *Sitzungsber. d.k. preuss. Akad. d. Wiss. z. Berlin*, I (1902), 126–28.

[2] O. Hecker, "Bestimmung der Schwerkraft auf dem atlantischen Ozean, sowie in Rio de Janeiro, Lissabon und Madrid, *Veröffentlichung d. k. preuss. Geod. Inst.* (N.F.), No. 11 (Berlin, 1903), pp. 84–85, Pl. 6.

[3] Measured in thousandths of a centimeter of acceleration.

cruise over the Black Sea, Hecker has now so revised his figures that they are no longer recognizable, and many of the excessive values for Δg. for one reason or another have disappeared altogether.[1] This is true, for example, for the third entry in the list quoted in table III. Hecker's methods have been more sharply challenged by Bauer[2] upon the ground that his instruments were

TABLE III

NORTH SEA AND BRITISH CHANNEL

Lat.	Long.	Δg. in cm.	Hecker's Mean
51°25′N.	3°50′E.	+0.053	−0.015
51 25 N.	3 40 E.	+0.016 } (0.134)*	
49 58 N.	1 1 W.	−0.118 }	
49 50 N.	1 17 W.	−0.035	
49 45 N.	2 29 W.	0.000	
49 39 N.	2 45 W.	−0.067	

* Author's interpolation.

TABLE IV

BETWEEN CAPE VERDE ISLANDS AND EQUATORIAL RIDGE

Lat.	Long.	Δg. in cm.	Hecker's Mean
11°52′ N.	26°57′ W.	−0.065	−0.038
11 44 N.	36 59 W.	−0.146 } (0.189)*	
10 54 N.	27 21 W.	+0.043 }	
10 44 N.	27 55 W.	+0.017	

* Author's interpolation.

not sufficiently standardized and checked during the work, and because his methods were in other respects open to criticism. In his first paper Bauer has sought further to discredit Hecker's corrected figures upon the ground that the values for Δg. vary more widely from Hayford's than did those of the first series. This point of view is interesting as indicating that local anomalies in

[1] O. Hecker, "Bestimmung der Schwerkraft auf dem schwarzen Meere sowie neue Ausgleichung der Schwerkraftmessungen auf dem atlantischen, indischen und groszen Ozeane," *Veröffentl. d. Zentralbureaus d. Internationalen Erdmessung* (N.F.), No. 20 (Berlin, 1910), pp. 1–160, 4 pls. (especially pp. 151–60).

[2] L. A. Bauer, "On gravity determinations," etc., *Am. Jour. Sci.* (4), XXXI (1911), 1–18. See also Hecker's remarks on "Ocean Gravity Observations" (a reply to Hecker), *ibid.*, XXXIII (1912), 245–48.

gravity must be forced out of sight or be interpreted by specialists in the field of the exact sciences as evidence of inaccurate work.

Hecker's figures in general indicate large anomalies of gravity above submerged escarpments and near where seaquakes have been felt.—If it be assumed that the limit of error in Hecker's measurements is not too high, his data from the Atlantic (the earlier ones particularly) and from the Indian and Pacific oceans all show a maximum of anomaly above the steep slopes at the margins of the continental shelves, and in general above submerged escarpments. Examined with reference to recorded seaquakes the earlier data in particular are hardly less interesting. Above the escarpment off the mouth of the Tagus, where such excessive values were recorded, it is known that several ships received heavy shocks at the time of the Lisbon earthquake (Fig. 4). The measurement of 0.146 of defect in the British channel, where there is no visible evidence for defect of matter (this figure had nearly disappeared in the earlier table under the mean of 0.015, and had vanished completely from the later tables), is almost exactly above the spot at which a seaquake has been put on record by Rudolph[1]—the only recorded one upon his map within a radius of 500 miles. Other noteworthy correspondences between seismicity and abnormal gravity will be noticed upon comparing Hecker's figures with Rudolph's map.

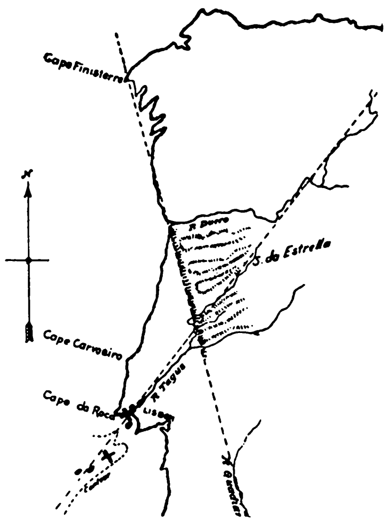

FIG. 4.—Sketch map of a portion of the Iberian Peninsula to indicate the great lineament of the Tagus, along which shocks were especially heavy at the time of the Lisbon earthquake of 1755. The positions of ships which felt the shock of the Lisbon earthquake are indicated, and also the two positions (crosses) where Hecker's measurements showed excessive values.

UNIVERSITY OF MICHIGAN
January, 1916

[1] E. Rudolph, "Über submarine Erdbeben und Eruptionen, mit Tafel iv–vii," *Gerlands Beiträge zur Geophysik*, I (1887), 133–365 (map at end).